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13. ABSTRACT (Maximum 200 words) The bulk results from the research can be found in Mr. Cedric Lam's Ph.D. dissertation, Multiple-wavelength Optical Coded-Division-Multiple-Access Communication Systems, published by UCLA in 1999. The main principle of optical CDMA is similar to radio CDMA. Instead of transmitting signals using only the necessary bandwidth, the signal energy is spread over a frequency spectrum, much broader than required to carry the information, by an encoding operation.					
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Multi-Wavelength Optical Code-Division-Multiplexing

Based on Passive, Linear, Unitary Filters

Final Technical Report

Principal Investigator: Eli Yablonovitch

Period Covered: 9/30/95-11/29/98

U.S. Air Force/Office of Scientific Research

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Objectives:

This project aims at finding the most practical way to implement Tera-bit optical code-division-multiple-access (OCDMA) communication and switching systems for future band-width demanding network applications.

Background:

The idea of spread spectrum communication and code division multiple access (CDMA) has been used in radio frequency domain to provide secure communication service and enable more efficient bandwidth sharing among cellular mobile phone users. In the past 10 to 15 years, there has been tremendous interest in applying similar concepts to optical communication systems.

Optical fiber communication channel, however, has very different characteristics compared to radio communication channel. Usually, optical fiber communication systems are much less sophisticated than their radio counterparts. The original idea of applying CDMA to optical communication systems was to use the existing bandwidth available in optical fiber, which was not readily accessible by the information streams, to perform some processing such as multiplexing and demultiplexing. Therefore, one can alleviate the electronic process overhead and hence overcome the electronic bottleneck in an opto-electronic communication system.

The proliferation of Internet, in particular due to the popularity of World Wide Web and e-commerce, has significantly increased the bandwidth demand in today's communication systems. As a result, a lot of advancement has been introduced into optical communication systems. On the one hand, point-to-point link capacity in backbone long distance communication systems has reached the terabit region. A 3-Terabit-per-second demonstration was reported in the 1999 Optical Fiber Communication (OFC '99) conference in San Diego. On the other hand, the penetration of optical fiber to business and households is deeper and deeper. Local optical access systems making use of low-cost technologies such as vertical cavity surface emitting lasers (VCSEL's) and multi-mode fibers will eventually make fiber to the home (FTTH) and fiber to the desk (FTTD) a reality.

Every hertz of bandwidth available in optical fiber is now valuable for carrying data traffic in contemporary communication systems. A different paradigm is required in designing multiple access optical communication systems to meet the challenges in current and future networks. It is important for a multiple access network to provide the access to the full bandwidth available in optical fiber, in addition to enable different users to share a common, high capacity communication channel. Wavelength division multiplexing (WDM) has emerged as a powerful approach to unlock capacity in an optical fiber. In this project, we studied an alternative approach, i.e. CDMA in optical fiber networks. Its advantages, limitations and the possible benefit of properly designed OCDMA systems were investigated.

Executive Summary:

The bulk results from this research can be found in Mr. Cedric Lam's Ph.D. dissertation, *Multiple-wavelength Optical Coded-Division-Multiple-Access Communication Systems*, published by UCLA in 1999.

The main principle of optical CDMA is similar to radio CDMA. Instead of transmitting signals using only the necessary bandwidth, the signal energy is spread over a frequency spectrum, much broader than required to carry the information, by an encoding operation. The receiver recovers the channel signal by correlating the received signal with the same code used for encoding. Incorrectly encoded signals are rejected by the correlation operation owing to code orthogonality. Spread spectrum encoding increases the difficulty of eavesdropping, therefore, enhancing the system security. All the spread spectrum signals share the same bandwidth and are distinguished by their codes. This is different from other systems, such as time division multiple access (TDMA) and WDM systems in which channels occupy non-overlapping time or frequency slots and are separated by guard time or guard bands to prevent crosstalk. CDMA systems allow users to share the full time-frequency space, eliminating the necessity of guard times and guard bands. On the other hand, the channels sharing the same time-frequency space will interfere with one another if not properly designed.

Despite the similarity in principle, OCDMA systems are very different from their radio counterparts because of the differences between optical fiber channel and radio channel. Intensity modulation and detection has been established as the most practical way of performing optical communication, whereas in radio communication systems, electrical field modulation and detection have been widely adopted.

To obtain good performance, one needs orthogonality between channels to minimize crosstalk. Real orthogonality is only achievable when both positive and negative quantities are available. A lot of orthogonal code families have been designed for radio spread spectrum systems. Contrary to electric field, which is bipolar, the intensity signal used in optical communications is a positive-only quantity. This presents some challenge in designing orthogonal OCDMA codes.

Besides code orthogonality, speckle noise and shot noise are the two other very fundamental and important issues in OCDMA systems, which will directly impact the performance. The trick to obtain the required negative quantity from positive intensity signals and to achieve full orthogonality is to use a balanced receiver. The output of a balanced receiver is the analog difference signals between two series connected photodetectors and can be both positive and negative. As a result, the integrated output from a balanced receiver over each bit period or over a spectral range can be made zero.

In this project, we studied two spectral encoding approaches. The first approach is a spectral intensity encoded system. In this fully non-coherent system, each channel

uses a pair of complementary encoded spectra to transmit the 0 and 1 bits. The receiver matches the complementary encoded spectra to the two photodetectors in the balanced receiver respectively. This results in bipolar signaling at the receiver. A novel balanced transmitter has been invented for this approach. It consists of two broad band optical sources connected in series as in a balanced receiver. The two sources are differentially modulated by binary input data to generate complementary spectrally encoded output.

Two experimental demonstrations were performed for spectral intensity encoded systems. In the first demonstration, we used as a multi-wavelength laser diode array, commercial WDM MUX-DEMUX and 2×2 optical switches to make a fully configurable Hadamard encoder. In the second demonstration, the spontaneous emission spectrum of an Erbium doped fiber amplifier (EDFA) has been used the broadband source, a novel cascaded Mach-Zehnder encoder custom fabricated by Photonic Integrated Research Inc. (PIRI) has been employed. Full orthogonality has been demonstrated in both experiments.

The performance of spectral intensity encoded systems has been analyzed. Apart from the usual thermal noise, a few other mechanisms contribute to signal degradation. The biggest noise is due to coherent signal interference generated by transmitters sharing the same wavelengths and transmitting simultaneously. This produces large fluctuations of signal intensity at the receiver photodetector because of constructive and destructive interference. Similar interference mechanism also gives rise to spatial power fluctuation in a laser output called speckles. Therefore, the noise due to coherent interference is also called speckle noise.

Since speckle noise is proportional to the signal power, increasing the signal power will not improve the signal to noise ratio. In order to improve the performance, one has to use a wider optical bandwidth to get the spectral averaging effect. In the presence of multiple users, the interference due to speckle noise increases as the square of the number of co-active users and forms the performance limitation.

The spontaneous emission source used in the system also introduces spontaneous emission noise, which is analogous to speckle noise except that it arises from multiple Er atoms rather than multiple users.

Interference also arises from cumulative shot noise. The detectors in an OCDMA receiver detect the aggregate of the signals from all the users transmitting in the network. Optical signal detection is associated with shot noise due to the particle nature of light. Even though the balance receiver is able to cancel the signal from co-channel users, the shot noise will never cancel and is added at the receiver output. Since shot noise goes as the square root of signal power, the signal to noise ratio is improved by increasing the signal strength. Cumulative shot noise is proportional to the total number of co-active users in the system. Usually, speckle noise is more important than cumulative shot noise.

To overcome speckle noise, we proposed a new OCDMA system that uses spectral phase encoding of a mode-locked laser output. By properly encode the phases of the spectral components in a mode-locked laser output and synchronize the transmitters to the mode-locked pulse duration, one can avoid speckle interference noise. Nevertheless, cumulative shot noise cannot be avoided and will eventually set the limit to system performance. As mentioned before, it is possible to overcome shot noise by increasing the signal strength. Calculation showed that with reasonably large transmission power, a total throughput around in the order of Tera-bits per second is possible.

A novel cascaded feedback Mach-Zehnder OCDMA encoder has been proposed and analyzed for the spectral phase encoded system. It was shown that to produce a code of N wavelengths, an encoder of $\text{Log}_2 N$ complexity is required. Besides CDMA systems, we also compared the general demultiplexing complexities in TDM, WDM and CDM systems. It was shown that with properly designed demultiplexing components, logarithmic demultiplexing complexity could be achieved in all three types of multiple access systems. A new logarithmic WDM filter was hence proposed and simulated in this program. This WDM filter has the potential of integrated photonics.

In the course of pursuing OCDMA research, we also paid close attention to WDM systems. WDM appears to be a natural way of multiplexing signals on an optical fiber. Due to the fact that WDM channels occupy disjoint frequency slots in the optical spectrum and the receiver only detect the frequency slot of interest for each channel, WDM systems do not experience speckle noise interference and cumulative shot noise. However, significant guard bands exist in WDM systems due to the difficulties to produce rectangular shaped WDM filters. This makes the available optical spectrum heavily underutilized. In fact, one reason to study CDMA systems is to try to make uniform spectral utilization through bandwidth sharing.

Given the advantages of WDM systems and their fast growing popularity, a new approach to implement ultra-dense WDM systems with almost zero guard band requirement has been proposed. This new WDM approach, in conjunction with multi-level signaling used in modern radio communication systems and optical single side band modulation, is expected to improve the bandwidth efficiency by 100 fold in future fiber optic communication systems. These ideas have been compiled into the white paper *Tandem Single-Side-Band Optical Communications Using 100%-Dense WDM and Quadrature Amplitude Modulation (QAM) for a 100X Increase in Communications Capacity*, in response to DARPA solicitation BAA-99-06 on *Next Generation Internet (NGI)* proposals. A two-year research grant has been awarded for the proposed idea.

We conclude that security might be the biggest advantage of OCDMA systems. The encoding at the physical layer maybe useful for systems which need security but cannot afford the encryption delays, such as voice and motion picture transmission. Of course, various levels of security can be built into a system. A combination of physical layer encoding such as OCDMA combining with other security techniques can render a system extremely secure to heckers and eavesdroppers.

To obtain ultimate network throughput, OCDMA is still hard to compete with WDM. However, if one can find a very low cost implementation of OCDMA encoders and decoders, there might be a chance that this technology could be useful as an option for fiber in the loop (FITL) or low cost optical local area networks (LAN's).

Accomplishment / New Findings

- (1) Demonstrated spectral intensity encoded OCDMA systems using both commercial components and a novel cascaded Mach-Zehnder encoder.
- (2) Proposed and demonstrated a novel balanced transmitter for complementary spectral intensity encoding.
- (3) Proposed and demonstrated a cascaded Mach-Zehnder OCDMA encoder to generate complementary spectral codes.
- (4) Analyzed the performance of non-coherent spectral intensity encoded OCDMA systems due to speckle noise and cumulative shot noise limitation.
- (5) Proposed a spectral phase encoded OCDMA system, which is not limited by speckle noise. The system performance due to cumulative shot noise limitation was analyzed.
- (6) Showed that logarithmic demultiplexing complexity is achievable in CDM, TDM and WDM systems.
- (7) Proposed and simulated a rectangular shaped WDM filter, which can be cascaded to make a WDM demultiplexer with logarithmic scaling complexity. The proposed filter uses a 1-D photonic crystal structure.
- (8) Proposed a new WDM technology to fully utilize the available optical spectrum without guard band reservations. The idea has been formulated into a DARPA proposal, which has been awarded.

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- Faculty: Eli Yablonovitch, Harold Fetterman, Ming Wu, Izhak Rubin
- PostDoc: Ji-Lin Shing
- Graduate Student Researchers : Cedric Lam, John Siwko, Ms. Jing Ling, Dennis Tong, Shamino Wang, D.P. Prakash

Publications:

1. C.F. Lam, R.B. Vrijen, D.T.K. Tong, M.C. Wu and E. Yablonovitch, "Multi-wavelength Spectrally Encoded Optical Code Division Multiple Access Communication Systems", in preparation.
2. C.F. Lam, *Multi-wavelength Optical Code-Division-Multiple-Access Communication Systems*, Ph.D. Dissertation, UCLA, 1999.
3. C.F. Lam, R. Vrijen, D.T.K. Tong, M.C. Wu and E. Yablonovitch, "Multi-wavelength Optical Code Division Multiplexing", (Invited paper), *Critical Reviews of*

- Optical Science and Technology on Wavelength Division Multiplexing*, SPIE Photonics West '99, Jan 1999, San Jose, California.
4. C.F. Lam and E. Yablonovitch, "Multi-wavelength Optical Code Division Multiplexing", To appear in *Future Trends in Microelectronics: Off the Beaten Path*, John Wiley, 1999.
 5. C.F. Lam, D.T.K. Tong, M.C. Wu and E. Yablonovitch, "Experimental Demonstration of Bipolar Optical CDMA System Using a Balanced Transmitter and Complementary Spectral Encoding", *IEEE Photonics Technology Letters*, Vol. 10, No. 10, pp1504-1506, Oct. 1998.
 6. C.F. Lam, R.B. Vrijen, P. Chang-chien, D. Sievenpiper and E. Yablonovitch, "A Tunable Wavelength Demultiplexer Using Logarithmic Filter Chains", *IEEE/OSA Journal of Lightwave Technology*, Vol. 16, No. 9, pp1657-1662, Sep. 1998.
 7. C.F. Lam, R. Vrijen, D.T.K. Tong, M.C. Wu and E. Yablonovitch, "Experimental Demonstration of Spectrally Encoded Optical CDMA System Using Mach-Zehnder Encoder Chains", paper CThU4, *IEEE/OSA CLEO'98*, May 1998, San Francisco.
 8. D.F. Sievenpiper, C.F. Lam, E. Yablonovitch, "Two-Dimensional Photonic- Crystal Vertical-Cavity Array for Nonlinear Optical Image Processing", *Applied Optics*, Vol. 37, No. 11, pp2074-2078, 10 Apr. 1998.
 9. C.F. Lam, R.B. Vrijen, P. Chang-chien, D. Sievenpiper and E. Yablonovitch "A Tunable Wavelength Demultiplexer Using Cascaded Photonic-Crystal Filters", *OSA Optics & Photonics News*, Jan. 1998, Vol. 9, No. 1, pp49.
 10. C.F. Lam and E. Yablonovitch, "Shot-noise-induced Crosstalk in Spectrally Encoded Optical CDMA Systems", Paper FM2 in *OSA Annual Meeting*, October 12-17, 1997, Long Beach, CA.
 11. C.F. Lam and E. Yablonovitch, "A Fast Wavelength Hopped CDMA System for Secure Optical Communications", *Proc. SPIE Conference on Computer and Network Security*, Nov. 1997, Dallas, Texas.
 12. C.F. Lam, R. Vrijen, D.T.K. Tong, M.C. Wu and E. Yablonovitch, "Spectrally Encoded CDMA System Using Mach-Zehnder Encoder Chains", *Proc. SPIE Conference on Computer and Network Security*, Nov. 1997, Dallas, Texas.
 13. C.F. Lam and E. Yablonovitch, "A Configurable Wavelength Demultiplexer Using Periodic Filter Chains", *1997 Digest of the LEOS Summer Topical Meetings*, Montreal, Canada, IEEE.
 14. C.F. Lam and E. Yablonovitch, "Terabit Switching and Security Enhancement in a WDM/TDM Hybrid System", *1997 Digest of the LEOS Summer Topical Meetings*, Montreal, Canada, IEEE.
 15. D.P. Prakash, D.C. Scott, H.R. Fetterman, M. Matloubian, Q. Du and W. Wang, "Integration of Polyimide Waveguides with Traveling-Wave Phototransistors", *Photonics Tech. Letters*, v9, pp800 to 805, June 1997.
 16. D. T. K. Tong and M. C. Wu, "Multiwavelength Microwave Photonic Systems: Beyond Fundamental RIN-Limited Performance," *1997 Conference of Lasers and Electro-Optics (CLEO)*, Paper CWN4, Baltimore, Maryland, May 18 - 23, 1997.
 17. D. T. K. Tong and M. C. Wu, "Multiwavelength Optically Controlled Phased Array Antennas," *1997 Progress in Electromagnetics REsearch Symposium (PIERS'97)*, Cambridge, Massachusetts, July 7 - 11, 1997.

18. I. Rubin and H.K. Hua, "Synthesis and Throughput Behavior of WDM Meshed-Ring Networks under Nonuniform Traffic Loading," *Journal of Lightwave Technology*, IEEE/OSA, Vol. 15, No. 8, pp. 1513-1521, August 1997.
19. I. Rubin and J. Ling, "Survivable all-optical cross-connect meshed ring communications networks," *SPIE Conference on Computer and Network Security*, Nov. 1997.
20. J. Siwko and I. Rubin, *Call Admission Control Policies for Capacity Varying Communications Networks*, UCLA technical report, 1997.
21. D. T. K. Tong and M. C. Wu, "Programmable Dispersion Matrix Using Bragg Fiber Grating for Optically Controlled Phased Array Antennas," *Electronics Letters*, Vol. 32, No. 17, pp. 1532-1533, August, 1996.
22. Moghe, P., Rubin, I. "Enhanced Call: A Paradigm for Applications with Dynamic Client-membership and Client-Level binding in ATM Networks," *IEEE/ACM Transactions on Networking*, Vol. 4, No. 4, pp. 615-628, August 1996.
23. Baker, J., Rubin, I., Multiple Access Communications, a Chapter in the *Encyclopedia of Telecommunications*, Froelich, Ed., Marcel Dekker, Inc. publications, Vol. 12, 1996.
24. Rubin, I., and Wu, H. T., "Performance Analysis and Design of CQBT Algorithm for a Ring Network with Spatial Reuse," *IEEE/ACM Transactions on Networking*, Vol. 4, No. 4, pp. 649-659, August 1996.
25. D. T. K. Tong and M. C. Wu, "A Novel Multiwavelength Optically Controlled Phased Array Antenna with a Programmable Dispersion Matrix" *IEEE Photonics Technology Letters*, Vol. 8, No. 6, pp. 812-814, June 1996.
26. D. T. K. Tong, N. A. Bhatt, and M. C. Wu, "Novel Optoelectronic Technique for Tunable Millimeter-Wave Generation Using a Monolithic Mode-Locked Semiconductor Laser," *1996 Conference of Lasers and Electro-Optics (CLEO'96)*, Paper CTuD6, June 3 - 7, 1996.
27. D. T. K. Tong and M. C. Wu, "Programmable-Dispersion Matrix for Optical Beam Forming Network," *1996 Conference of Lasers and Electro-Optics (CLEO'96)*, Paper CWC6, June 3 - 7, 1996.
28. M. C. Wu and D. T. K. Tong, "A Programmable True-Time Delay Fiber Network for Multiwavelength Optically Controlled Phased Array Antenna," *GOMAC'96*, Paper 15.2, Kissimmee, Florida, March 18-21, 1996.
29. M. C. Wu, and D. T. K. Tong, "Novel Multiwavelength Optically Controlled Phased Array Antennas," *The ARPA Symposium on Photonic Systems for Antenna Applications (PSAA-6)*, Monterey, California, March 4-7, 1996.
30. Rubin, I., Wu, C.H., "Analysis of an M/G/1/N Queue with Vacations and its Iterative Application to FDDI Timed-Token Rings," *IEEE/ACM Transactions on Networking*, pp. 842-856, December 1995.
31. C.F. Lam and E. Yablonovitch, "Multi-wavelength, optical code-division-multiplexing based on passive, linear, unitary, filters", *Proceeding 1995 Int. Symposium on Signals, Systems and Electronics*, San Francisco, IEEE.
32. D. T. K. Tong and M. C. Wu, "A Novel Optically Controlled Phased Array Antenna System Using a Programmable-Dispersion Fiber and a Mode-Locked Laser," *IEEE*

LEOS Annual Meeting (LEOS'95), Paper EOS4.3, San Francisco, CA, October 30 - November 2, 1995.

33. Rubin, I., Hua, H.K., "SMARTNet: An All-Optical Wavelength-Division Meshed-Ring Packet Switching Network," *Proceedings IEEE GLOBECOM'95 Conference*, Singapore, Nov. 1995.
34. Rubin, I., Ratkovic, A., "Performance Analysis of ATM Switches under a Multi Mode Traffic Model," *Proceedings IEEE GLOBECOM'95 Conference*, Singapore, Nov. 1995.
35. Rubin, I., Moghe, P., "Enhanced Call: a Paradigm for Applications with Dynamic Client-Membership in ATM Networks," *Proceedings IEEE GLOBECOM'95 Conference*, Singapore, Nov. 1995.

References:

1. C.F. Lam, *Multi-wavelength Optical Code-Division-Multiple-Access Communication Systems*, Ph.D. Dissertation, UCLA, 1999.
2. E. Yablonovitch and M. Wu, *Tandem Single-Side-Band Optical Communication Using 100%-Dense WDM and Quadrature Amplitude Modulation (QAM) for a 100X Increase in Communication Capacity*, Proposal in response to DARPA BAA-99-06 "Extensible Networks and the Next Generation Internet", UCLA, 1999.